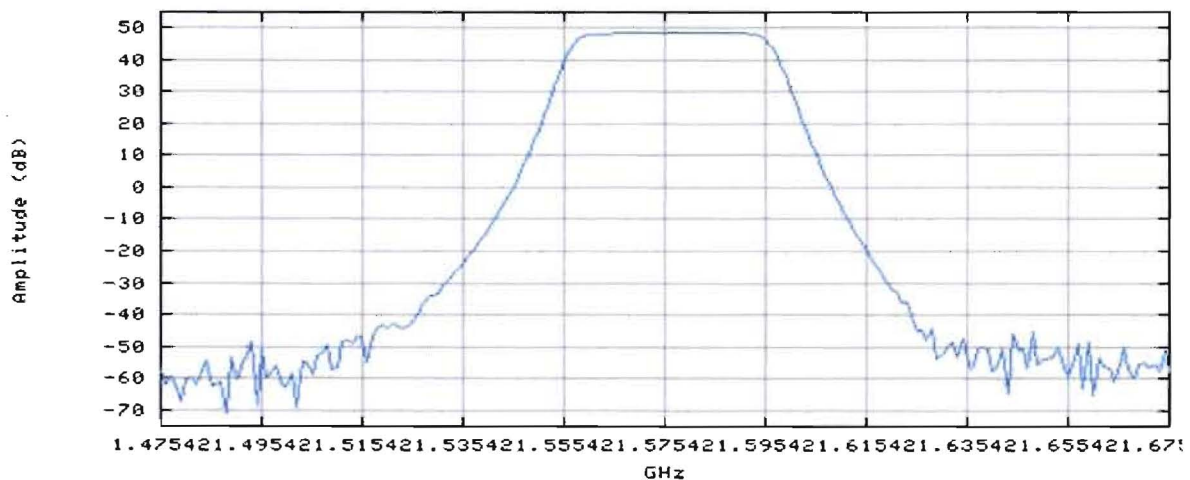### 3.1.1.2 Omni Directional Antenna Characteristics

WAAS Reference Stations (WRSs) and Ground Uplink Subsystems (GUSs) both utilize the NW2225 antenna. The requirements this antenna must satisfy are documented in unit and system level WAAS documentation. Table 1-3 provides an excerpt from this documentation for key L1 antenna requirements useful for evaluation of interference effects. Additionally, Figure 1-13 provides actual performance of the antenna's integrated Filter/LNA for frequencies near the L1 passband.

Table 1-3. Key L1 Antenna Characteristics for NW2225

Antenna pattern gain for RHCP signal Gain L1 Elevation = 5° Elevation = 90° (Zenith)	$\geq$ -9.0 dBic $\geq$ 3.0 dBic
Axial ratio	4.0 dB, Max.
RF Gain	48 ± 3 dB
Maximum Input Signal w/o Damage	+20 dBm, CW
1 dB Compression Point	+10 dBm, Min,
Noise Figure	$\leq$ 2.0 dB @25° C
Attenuation $\geq$ -80 dB Attenuation near L1 -80 dB	Non-operating frequencies @ $\pm$ 50 of 1575.42 MHz (Max)

Figure 1-13. WAAS Antenna (NW2225) L1 Signal Conditioning Performance

3.1.1.2 Downlink Antenna Characteristics

The GUS also uses a High Directional/High Gain antenna for receiving the L1 and L5 downlink signals from the WAAS GEO satellites. Key performance requirements for this antenna are reflected in Figure 1-14 where the max gain has been normalized to zero dB. The gain of the antenna at boresight is nominally 28 dB.
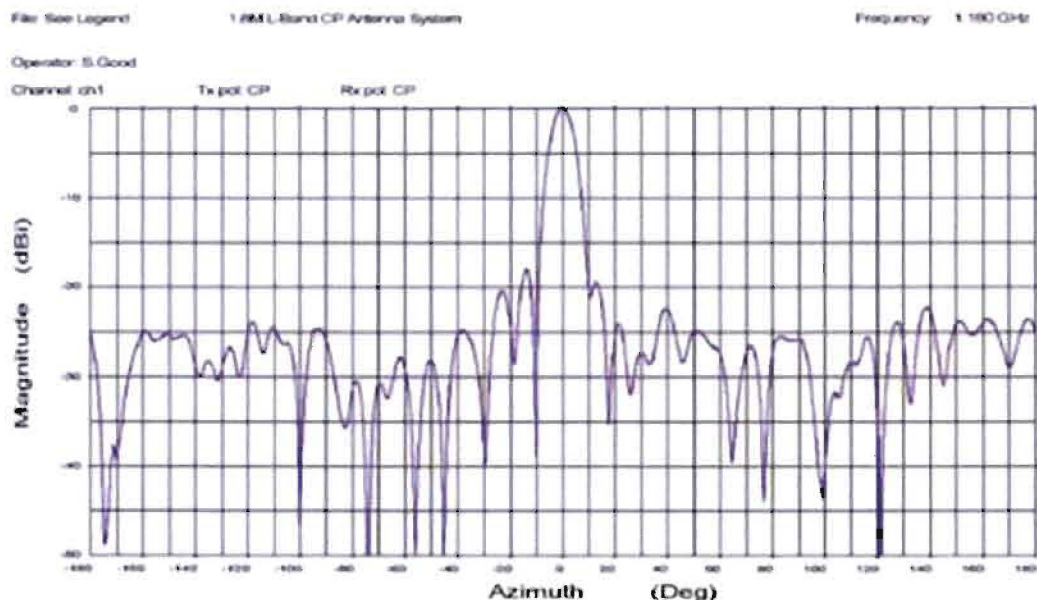

Figure 1-14. GUS Antenna Gain Pattern

3.1.2 WAAS Network Receivers

L1 signal processing provided by the receiver is essentially identical for reference station and ground uplink applications in WAAS. As with the WAAS antenna, signal processing requirements relevant to RF interference performance are documented in unit and system level WAAS documentation. This documentation contains other requirements too numerous to list in this document related to signal acquisition, accuracy and data demodulation performance. For receiver performance pertaining to interference, the specifications require the receiver provide filter attenuation for out-of-band emissions of 50 dB or greater. For out-of-band emissions within ± 50 MHz of the L1, L2 and L5 center frequencies, the receiver provides filter attenuation characteristics as specified in Figure 1-15. The receiver may achieve these attenuation characteristics through a combination of RF and IF filters.
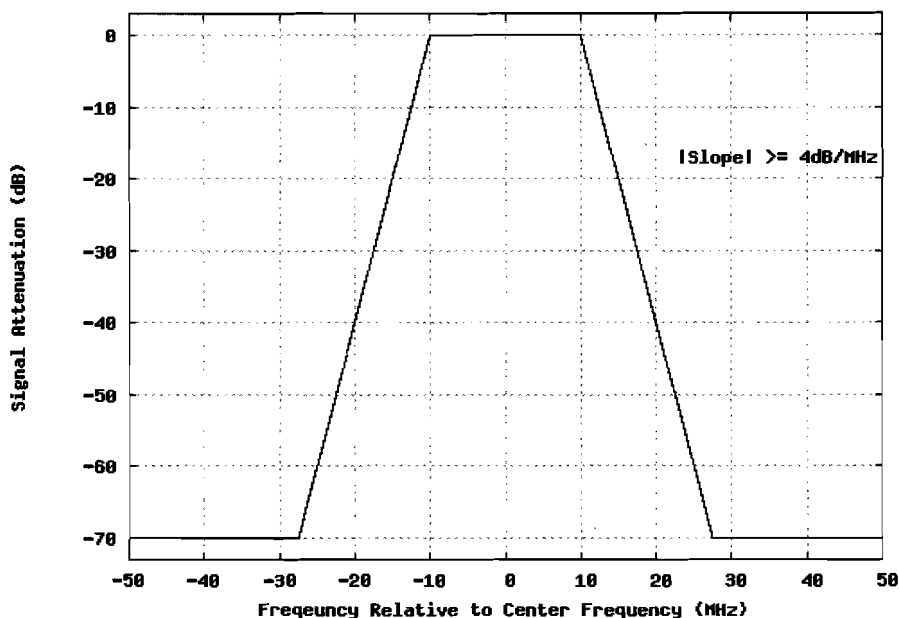
Figure 1-15. RF Attenuation Near L1 L2 and L5 Passbands

Out-of-band rejection characteristics are intended to be satisfied with the combination of antenna and receiver filtering and receiver processing gain. Therefore, after initial signal acquisition and steady-state operation has commenced with the receiver, a GPS/WAAS antenna/receiver can operate in the presence of a single CW interferer that does not exceed the interference to signal power ratio by more than the levels shown in Table 1-4 (further illustrated in Figure 1-16). The interference signal is relative to the minimum GPS/WAAS signal levels. The signal suppression allocations are as follows: 80 dB for the antenna filter, 50 dB for receiver out of band, and 24 dB for receiver in-band processing gain. Note that CW was specified for out-of-band emissions to constrain test requirements.

Table 1-4. Out of Band Rejection Characteristics

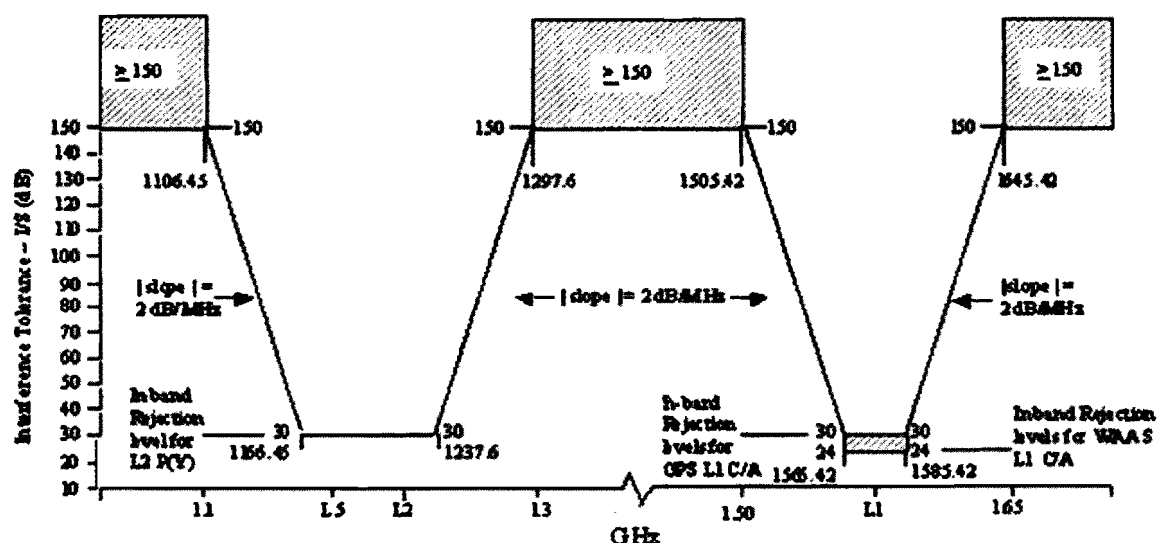| Interference Frequency, f (MHz)	Interference to Signal Power Ratio (dB)
800 < f ≤ 1106.45	≥150 dB
1106.45 < f ≤ 1166.45	+150 − 2*(f-1106.45) dB
1237.6 < f ≤ 1297.6	+30 + 2*(f - 1237.6) dB
1297.6 < f ≤ 1505.42	≥150 dB
1505.42 < f ≤ 1565.42	+150 - 2*(f-1505.42) dB
1585.42 < f ≤ 1645.42	+30 + 2*(f - 1585.42) dB
1645.42 < f < 2000 for L1	≥150 dB
1645.42 < f < 1700 for L2	≥150 dB

Figure 1-16. Out of Band Rejection Characteristics for CW Interference

3.2 GBAS

The U.S. GBAS program was originally referred to as the Local Area Augmentation System (LAAS) but recently changed in name to adhere to international terminology. A Category I (CAT I) Non-Federal GBAS built by Honeywell International received System Design Approval (SDA) from the FAA on September 3, 2009. The Port Authority of New York/New Jersey has purchased and installed the first system at Newark Liberty International Airport. This system is expected to become operational in the near future. Several different prototype systems are installed at other locations in the United States. The FAA's GBAS Program Office is working in conjunction with industry towards the operational validation of Category II/III GBAS standards and specifications.

Current CAT I Non-Federal GBASs conform to the specifications in [20], which provide numerous performance requirements that must be met with identical maximum interference levels as those in use for GPS avionics described earlier in this document.

3.3 Timing

GPS timing receivers are used for critical purposes at numerous facilities in the national airspace system (NAS). These include Trimble Resolution T receivers for the ADS-B stations being deployed by ITT. TrueTime and Symmetricom GPS timing receivers are used for timing for several automation systems. These are commercial timing products that should be covered by the TWG's timing receiver category.

1-20

4 Operational Scenarios

The following operational scenarios are extracted from [6]. For each operational scenario, all applicable performance requirements from [14, 16] must be met in the presence of both LightSquared emissions (considering constraints on the siting of the base stations near airports to protect mobile satellite services) and all known other interference sources as identified in [6].

4.1 En Route/Terminal Area

For the en route flight phase aircraft are generally constrained to be at an altitude of at least 500 feet above structures or terrain in uncongested areas and at least 1000 feet above structures or terrain in congested areas. In the terminal area on the initial approach segment the flight path is a minimum of 1000 feet above any obstacles. On the intermediate approach segment the flight path is a minimum of 500 feet above obstacles. In these phases of flight, GNSS may be used for horizontal guidance in IMC operations. For off-board sources, the minimum RFI source separation distance to the closest terrestrial source is defined as 500 feet.

4.1.1 En Route Acquisition

The aircraft in this scenario is assumed to have been in normal, en route GNSS navigation for a sufficient time to have up-to-date satellite ephemeris data, stored position, velocity, and receiver clock bias/drift information. Normal navigation is then somehow interrupted for a short time (e.g. by a momentary aircraft power failure) and the receiver must re-establish navigation by a full "warm-start" acquisition. For this scenario, the aircraft is assumed to be in level flight at a representative limiting-case altitude of 18,000 feet (5.5 km).

4.1.2 En Route Tracking/Data Demodulation

For the en route tracking / demodulation scenario, the aircraft is assumed to be in level flight at a representative limiting-case altitude of 18,000 feet (5.5 km) above ground level. Both GPS and SBAS (e.g., WAAS) satellite signals are considered. The usefulness of the SBAS signals for integrity and error correction depends on the aircraft position being within an area covered by SBAS ground reference stations. Certain components of total RFI vary as a function of location, (e.g., GNSS self-interference, terrestrial RFI). Given these two aspects, the en route GPS and SBAS scenario link analyses may be performed at different limiting-case locations.

4.1.3 Terminal Area Tracking/Data Demodulation

For this terminal area scenario, the aircraft is assumed to be in level flight with its GNSS antenna at an intermediate value between the en route and Category I precision approach scenarios. The airborne GPS antenna height is 1756 feet (535.2 m).

4.2 Non-precision Approach Tracking/Data Demodulation

For non-precision approach operations, [6] recommends using a 100 foot (30.5 m) separation to a ground-based obstacle (source of interference) and the Category I airborne antenna gain pattern below the aircraft (see Figure 1-8).

4.3 Category I Precision Approach Tracking/Data Demodulation

For category I (CAT I) precision approach, [6] recommends using a 96.7 foot (29.5 m) obstacle clearance surface (OCS) distance (distance to closest possible ground-based interference source) and a 175 foot (53.3 m) above-ground GNSS airborne antenna height.

4.4 Category II/III Precision Approach Tracking/Data Demodulation

For a CAT II/III precision approach, [6] recommends using a 70 foot (21.3 m) OCS distance (distance to closest possible ground-based interference source) and a 85.1 foot (25.9 m) above-ground GNSS airborne antenna height. Such operations require a CAT II/III GBAS to be installed at the airport.

4.5 Surface Acquisition and Tracking/Data Demodulation

This operational scenario encompasses surface operations where the aircraft is at the gate or taxiing. For this scenario, the GNSS aircraft antenna height is assumed to be 4 m (a nominal height for a regional or business jet). The aircraft is either stationary or in a slow taxi. GNSS receiver signal tracking and acquisition should be tested in the scenario.

5 Future Considerations

Work is currently underway domestically and internationally towards the development of multi-frequency, multi-GNSS standards. Such standards will support additional signals in the 1559 – 1610 MHz band, including the Galileo open service and GPS L1C signals that use a multiplexed binary offset carrier modulation (MBOC). The power spectral density of MBOC is much broader than the GPS L1 C/A-code and may require wider bandwidth avionics.

Future GNSS avionics, in order to accrue the benefits of new civil signals on other frequencies (e.g., GPS L5 at 1176.45 MHz), will require new airborne multi-band antennas. These will likely be stacked patch antennas, and it is possible that their gain performance at L1 will suffer in comparison to existing antennas. Additionally, in the future, GNSS avionics may be required to meet more demanding performance requirements. These factors, together, will tighten current slim margins on interference budgets (see, e.g., [6]) for airborne GNSS equipment.

REFERENCES:

[1]   FAA, *Passive Airborne Global Positioning System Antenna*, Technical Standard Order (TSO) C144a, Federal Aviation Administration, Washington, D.C., 30 March 2007. (This FAA regulatory document invokes the performance requirements in RTCA DO-228, Change 1).

[2]   RTCA, *Minimum Operational Performance Standards for Global Navigation Satellite System (GNSS) Airborne Antenna Equipment*, Washington, D.C., RTCA DO-228, including Change 1, January 11, 2000.

[3]   FAA, *Active Airborne Global Navigation Satellite System (GNSS) Antenna*, Technical Standard Order (TSO) C190, Federal Aviation Administration, Washington, D.C., 30 March 2007. (This FAA regulatory document invokes the performance requirements in RTCA DO-301).

[4]   RTCA, *Minimum Operational Performance Standards for Global Navigation Satellite System (GNSS) Airborne Active Antenna Equipment for the L1 Frequency Band*, Washington, D.C., RTCA DO-301, December 13, 2006.

[5]   ICAO, Annex 10 to the Convention of International Civil Aviation, Montreal, Canada, Jul. 12, 2010, vol. I, Radio Navigation Aids, Amendment 85.

[6]   RTCA, *Assessment of Radio Frequency Interference Relevant to the GNSS L1 Frequency Band*, Washington, D.C., RTCA DO-235B, March 13, 2008.

[7]   ARINC, *Global Navigation Satellite System (GNSS) sensor*, Annapolis, MD, ARINC Characteristic 743A-4, Dec. 2001.

[8]   FAA, Airborne Supplemental Navigation Equipment Using the Global Positioning System (GPS), Technical Standard Order (TSO) C129a, Federal Aviation Administration, Washington, D.C., 20 February 1996. (This FAA regulatory document invokes the performance requirements in RTCA DO-208, Change 1).

[9]   RTCA, *Minimum Operational Performance Standards for Airborne Supplemental Navigation Equipment Using Global Positioning System (GPS)*, Washington, D.C., RTCA DO-208, July 1991.

[10]   FAA, *Airborne Supplemental Navigation Sensors for Global Positioning System Equipment using Aircraft-Based Augmentation*, Technical Standard Order (TSO) C196, Federal Aviation Administration, Washington, D.C., 21 September 2009. (This FAA regulatory document invokes the performance requirements in RTCA DO-316).

[11]   RTCA, *Minimum Operational Performance Standards for Global Positioning System/Aircraft-based Augmentation System Airborne Equipment*, Washington, D.C., RTCA DO-316, 14 April 2009.

[12]   FAA, *Airborne Navigation Sensors Using the Global Positioning System Augmented by the Satellite Based Augmentation System*, Technical Standard Order (TSO) C145c, Federal Aviation Administration, Washington, D.C., 2 May 2008.

[13]   FAA, *Stand-Alone Airborne Navigation Equipment Using the Global Positioning System Augmented by the Satellite Based Augmentation System*, Technical Standard Order (TSO) C146c, Federal Aviation Administration, Washington, D.C., 9 May 2008.

[14]   RTCA, *Minimum Operational Performance Standards for Global Positioning System/Wide Area Augmentation System Airborne Equipment*, Washington, D.C., RTCA DO-229D, Dec. 13, 2006.

[15]   FAA, *Ground Based Augmentation System Positioning and Navigation Equipment*, Technical Standard Order (TSO) C161a, Federal Aviation Administration, Washington, D.C., 17 December 2009.

[16]   RTCA, *Minimum Operational Performance Standards for Global Positioning System Local Area Augmentation System Airborne Equipment*, Washington, D.C., RTCA DO-253C, December 16, 2008.

[17]   U.S. Air Force, GPS Directorate, Los Angeles Air Force Base, *Navstar GPS Space Segment/User Navigation User Interfaces*, El Segundo, CA, IS-GPS-200D, Mar. 2006.

2. Subtask 2 - Model Characterization of the Terrestrial Broadband Network

Task Statement

In cooperation with the LightSquared Working Group, develop a baseline model characterization of the planned initial and fully deployed broadband network, including ATC locations and siting assumptions/limitations. Identify user handset planning assumptions as appropriate.

LightSquared Ancillary Terrestrial Component (ATC) Technical Parameters

LightSquared plans for three spectrum phases for its broadcast signal:

- Phase 0: One 5 MHz channel : 1550.2 MHz- 1555.2 MHz, 62 dBm EIRP per 5 MHz channel

- Phase 1: Two 5 MHz channel : 1526.3 MHz -1531.3 MHz & 1550.2 MHz - 1555.2 MHz, 62 dBm EIRP per 5 MHz channel

- Phase 2: Two 10 MHz channel : 1526 MHz -1536 MHz & 1545.2 MHz - 1555.2 MHz, 62 dBm EIRP per 10 MHz channel

LightSquared has stated that their intention is to always operate ATCs at least 4 MHz away from the GPS band edge at 1559 MHz. Using LTE technology (OFDM, orthogonal frequency division multiplex modulation), each 10 MHz channel will have 1 MHz internal guard band, including 500 KHz on each side of the channel. LightSquared plans to deploy 20W per channel per sector. Each sector will have two transmit chains so a total power of 40W per sector per channel will be transmitted from each base station tower. Given there are three sectors, that results in a total of 120W per tower per channel. In LightSquared plans for spectrum Phases 1 and 2 there will be two channels so the result is 80W per sector or 240W per tower. Further, LightSquared plans to deploy a maximum of 62 dBm EIRP per channel and with two channels per sector, total EIRP per sector will then be 65 dBm per sector. Vertical cross polarization will be used for ATC transmissions.

Table 2-1. LightSquared Spectrum Deployment Phases

Development Phase	Channel Quantity and Size	Channel Locations	Nominal BTS Channel EIRP
Phase 0	One (1) 5MHz FDD	DL 1550.2-1555.2MHz UL 1651.7-1656.7 MHz	32 dBW (25 dBW/MHz)
Phase 1A	Two(2) 5MHz FDD	**Channel 1** DL 1526.3–1531.3MHz UL 1627.8-1632.8 MHz **Channel 2** DL 1550.2-1555.2 MHz UL 1651.7-1656.7 MHz	32 dBW (25 dBW/MHz)
Phase 2	Two(2) 10 MHz FDD	**Channel 1** DL 1526-1536 MHz UL 1627.5-1637.5 MHz **Channel 2** DL 1545.2-1555.2 MHz UL 1646.7-1656.7 MHz	32 dBW (22 dBW/MHz)

The distance between transmitters depends on type of morphology around each site as well as other capacity and coverage considerations. The maximum number of LightSquared network handsets a single ATC tower can support depends on the demand and service profile of each mobile device / handset, a typical site with two 10MHz channels can support 1200 users in active state and a much higher number in dormant state. LightSquared expects that the distance between transmitters would typically be:

- Dense urban environment: 0.4-0.8 km

- Urban environment: 1-2 km

- Suburban environment: 2-4 km

- Rural environment: 5-8 km

LightSquared User Handset Technical Parameters

When communicating with LightSquared towers, LightSquared mobile devices will transmit in L-band (1626.5 MHz -1660.5 MHz). LightSquared intends to use 10% of the total channel bandwidth as a guard band. For example, each 10 MHz channel will have 1 MHz guard band; 500 kHz on each side of the channel. LightSquared anticipates that some future devices may also utilize additional terrestrial cellular bands for transmission, but the specific bands are not yet confirmed. Linear polarization will be used for handset transmissions, with a maximum 23 dBm EIRP.

ATCt Mobile Terminal

- Maximum fundamental EIRP: -7 dBW

- Maximum unwanted EIRP: -90 dBW/MHz (1559-1605 MHz)

- Modulation: LTE (OFDM), 5 MHz occupied bandwidth

- Carrier frequency: 1654.2 MHz

- Antenna height: 1.8 m (est.)

As with the ATC, LightSquared plans three spectrum phases for its user handsets:

- Phase 0: One 5 MHz channel: 1651.7 MHz - 1656.7 MHz, 23 dBm maximum EIRP per user and smallest bandwidth a user can transmit is 180 KHz

- Phase 1: Two 5 MHz channels: 1627.8 MHz - 1632.8 MHz & 1651.7 MHz - 1656.7 MHz, 23 dBm maximum EIRP per user and smallest bandwidth a user can transmit is 180 KHz

- Phase 2: Two 10 MHz channels: 1627.5 MHz - 1637.5 MHz & 1646.7 MHz - 1656.7 MHz, 23 dBm maximum EIRP per user and smallest bandwidth a user can transmit is 180 KHz
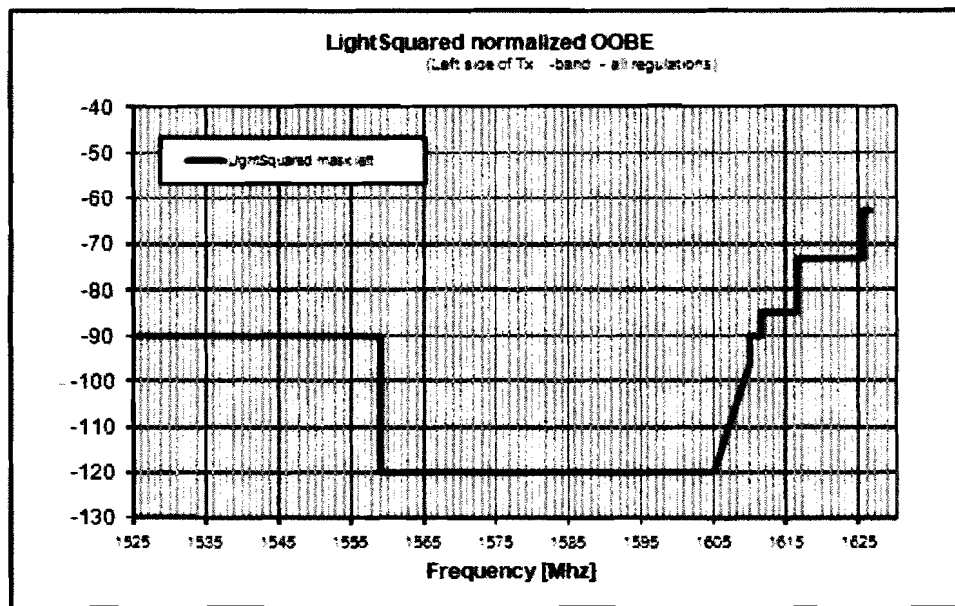
Figure 2-1. LightSquared OOBE requirements (normalized dBm/Hz from 1626.5 MHz) for LTE 10 MHz
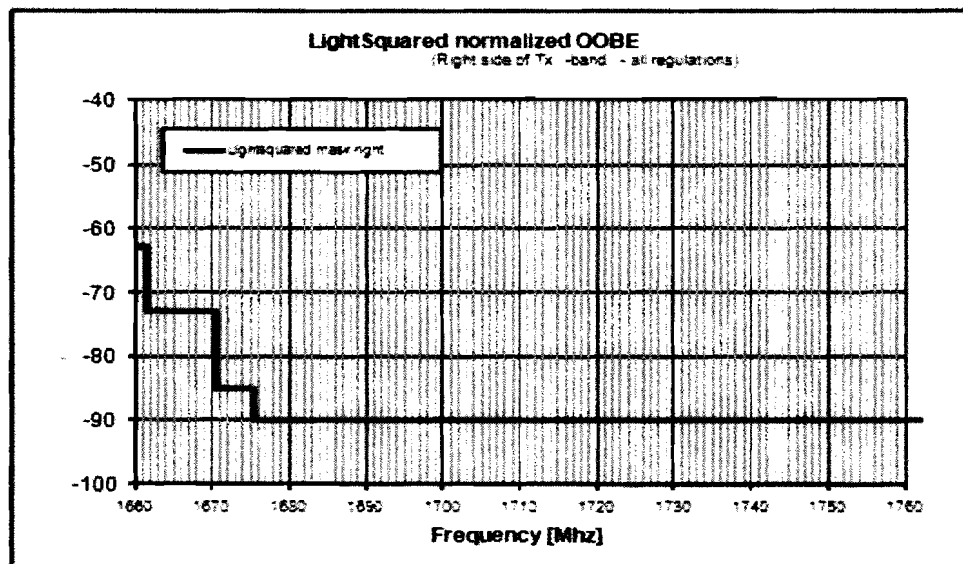

Figure 2-2. LightSquared OOBE requirements (normalized to dBm/Hz from 1660.5 MHz) for LTE 10 MHz

3. Subtask 3 - RF Interference in Operational Scenarios

Task Statement

In conjunction with federal and commercial GPS technical experts, develop operational scenarios representative of the full range of anticipated effects to GPS receiver use (including characterization by existing GPS receiver categories where possible) as well as deployed federal and commercial GPS-dependent systems or networks. The scenarios assessed shall consider federal and state government and commercial communities' current and planned use of GPS and GPS applications.

Operational Scenarios

Aviation

The following operational scenarios are extracted from [6]. For each operational scenario, all applicable performance requirements from [14, 16] must be met in the presence of both LightSquared emissions (considering constraints on the siting of the base stations near airports to protect mobile satellite services) and all known other interference sources as identified in [6].

En Route/Terminal Area

For the en route flight phase aircraft are generally constrained to be at an altitude of at least 500 feet above structures or terrain in uncongested areas and at least 1000 feet above structures or terrain in congested areas. In the terminal area on the initial approach segment the flight path is a minimum of 1000 feet above any obstacles. On the intermediate approach segment the flight path is a minimum of 500 feet above obstacles. In these phases of flight, GNSS may be used for horizontal guidance in IMC operations. For off-board sources, the minimum RFI source separation distance to the closest terrestrial source is defined as 500 feet.

En Route Acquisition

The aircraft in this scenario is assumed to have been in normal, en route GNSS navigation for a sufficient time to have up-to-date satellite ephemeris data, stored position, velocity, and receiver clock bias/drift information. Normal navigation is then somehow interrupted for a short time (e.g. by a momentary aircraft power failure) and the receiver must re-establish navigation by a full "warm-start" acquisition. For this scenario, the aircraft is assumed to be in level flight at a representative limiting-case altitude of 18,000 feet (5.5 km).

En Route Tracking/Data Demodulation

For the en route tracking / demodulation scenario, the aircraft is assumed to be in level flight at a representative limiting-case altitude of 18,000 feet (5.5 km) above ground level. Both GPS and SBAS (e.g., WAAS) satellite signals are considered. The usefulness of the SBAS signals for integrity and error correction depends on the aircraft position being within an area covered by SBAS ground reference stations. Certain components of total RFI vary as a function of location,

(e.g., GNSS self-interference, terrestrial RFI). Given these two aspects, the en route GPS and SBAS scenario link analyses may be performed at different limiting-case locations.

Terminal Area Tracking/Data Demodulation

For this terminal area scenario, the aircraft is assumed to be in level flight with its GNSS antenna at an intermediate value between the en route and Category I precision approach scenarios. The airborne GPS antenna height is 1756 feet (535.2 m).

Non-precision Approach Tracking/Data Demodulation

For non-precision approach operations, [6] recommends using a 100 foot (30.5 m) separation to a ground-based obstacle (source of interference) and the Category I airborne antenna gain pattern below the aircraft.

Category I Precision Approach Tracking/Data Demodulation

For category I (CAT I) precision approach, [6] recommends using a 96.7 foot (29.5 m) obstacle clearance surface (OCS) distance (distance to closest possible ground-based interference source) and a 175 foot (53.3 m) above-ground GNSS airborne antenna height.

Category II/III Precision Approach Tracking/Data Demodulation

For a CAT II/III precision approach, [6] recommends using a 70 foot (21.3 m) OCS distance (distance to closest possible ground-based interference source) and a 85.1 foot (25.9 m) above-ground GNSS airborne antenna height. Such operations require a CAT II/III GBAS to be installed at the airport.

Surface Acquisition and Tracking/Data Demodulation

This operational scenario encompasses surface operations where the aircraft is at the gate or taxiing. For this scenario, the GNSS aircraft antenna height is assumed to be 4 m (a nominal height for a regional or business jet). The aircraft is either stationary or in a slow taxi. GNSS receiver signal tracking and acquisition should be tested in the scenario.

Cellular

Cellular Telephone AGPS Use Cases

The three primary use case examples for GPS receivers in cellular telephones are: E911 Location; Location-Based Services; and Real-Time Navigation. This is not an all-inclusive list, but the three groups above are representative of typical AGPS use in the context of cellular telephones. Each of these three use cases is associated with unique signal level and propagation aspects, driven, in part, by device orientation and proximity to the user.

E911 Location

During an E911 call, the cellular telephone is expected to obtain a fix within 20 seconds to an accuracy of 50 meters 67% of the time and an accuracy of 150 meters 95% of the time. These performance criteria are in alignment with FCC E911 requirements. During an E911 call, the cellular telephone must be capable of meeting the location accuracy requirements described above while the device is held to the user's ear, which may affect the manufacturer's selection of antenna design and location.

Location-Based Services (LBS)

This use case provides cellular telephone users with information concerning businesses, activities, events, etc., located or taking place near the user's current location. Typically, in this use case the cellular telephone is oriented such that the display is easy to read, which may imply that the GPS antenna is facing away from the sky.

Real-Time Navigation

This use case allows the user to utilize his cellular telephone as a navigation device. Like location-based services above, the cellular telephone will typically be oriented such that it does not have a direct view of the sky. In addition, the cellular telephone may be situated inside a moving vehicle where the GPS signal strength is further compromised and fading is prevalent.

Cellular Telephone Non-AGPS Use Case

E911 Roaming

In instances where a cellular telephone is roaming onto another system, the telephone may not be able to receive network assist information from the roaming network. In these instances, E911 location information is determined by the cellular phone in an independent fashion using GPS in an autonomous mode.

General Location/Navigation

PND Use Case 1: Suburban

Suburban, tree lined environment mounted on dash of vehicle. Frequent changes of direction, obscuration of signals by the roof of the car, signal attenuation through windscreen, mild dynamics. Unit needs the ability to lock on to the correct road and navigate turns successfully. Need to distinguish between adjacent roads and ramps.

PND Use Case 2

Urban Canyon Urban canyon environment mounted on dash of vehicle. Frequent changes of direction, obscuration of signals by the roof of the car, blockage of satellites in view by tall buildings, signal attenuation through windscreen, mild dynamics. Unit needs the ability to lock

on to the correct road and navigate turns successfully. Need to distinguish between adjacent roads and ramps.

Outdoor Use Case: Golfing

Open area environment. Unit is held in the hand of a user who is walking and standing. Some dynamics associated with walking with the device, partial obscuration of signals by user's body. Unit needs the ability to measure distance, track user's position, and navigate to waypoints successfully.

Outdoor Use Case: Deep Forest

Deep forest environment. Unit is held in the hand of a moving user. Some dynamics associated with walking with the device, obscuration of signals by forest canopy and body of user. Unit needs the ability to measure distance, track user's position, and navigate to waypoints successfully.

Fitness Use Case: Arm Swing Environment

Unit under test mounted on the arm of a user who is swinging their arms in a manner consistent with distance running. The unit will experience frequent heading changes and the signal will be obscured by the body at times. Stressful dynamics are associated with the arm swing. Unit needs the ability to measure distance, track user's position/velocity, and navigate to waypoints successfully.

High Precision and Precision Timing Receivers

The only operational scenario for High Precision GPS usage is stationary and would primarily reflect the distance between the LightSquared base station transmitter and the GPS receiver. The distance at which unacceptable interference would occur would be the primary consideration for High Precision GPS receivers.

Type 1: Single point mode (no Augmentation)

- Performance Measures:
- Time To First Fix (s)
- Position accuracy (m)
- Velocity accuracy (m/s)
- Time accuracy (ns)
- PVT availability (% of time, or coverage area)

Type 2: WAAS Augmentation

- Time To First Fix (s)
- Position accuracy (m)
- Velocity accuracy (m/s)
- Time accuracy (ns)
- PVT availability (% of time, or coverage area)

Type 3: DGPS+RTK (code and carrier)

- Time To First Fix (s)
- Position accuracy (m)
- Velocity accuracy (m/s)
- Time accuracy (ns)
- PVT availability (% of time, or coverage area)

Networks

The performance characteristics of networks vary greatly by network type. This information is still being gathered. *(See the final TWG Report on 15 June 2011 for this information).*

Space-Based Receivers

Terrestrial-based scenario:

The BlackJack family of space-based receivers are each ground tested using rooftop antennas at the Jet Propulsion Laboratory for performance and burn-in for approximately 2000 hours before launch. Testing can also occur at various sites throughout the U.S. where spacecraft integration is accomplished.

Space-based Scenario:

A "worst case" scenario after launch has the occultation antenna, with up to 18 dBi antenna gain, directed toward the earth limb at the Eastern 1/3 of the continental USA. Six satellites are planned for an orbit at 520 km altitude, 24 degrees inclination, with six more at 800 km and 72 degrees.

REFERENCES:

[1]   FAA, *Passive Airborne Global Positioning System Antenna*, Technical Standard Order (TSO) C144a, Federal Aviation Administration, Washington, D.C., 30 March 2007. (This FAA regulatory document invokes the performance requirements in RTCA DO-228, Change 1).

[2]   RTCA, *Minimum Operational Performance Standards for Global Navigation Satellite System (GNSS) Airborne Antenna Equipment*, Washington, D.C., RTCA DO-228, including Change 1, January 11, 2000.

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[6]   RTCA, *Assessment of Radio Frequency Interference Relevant to the GNSS L1 Frequency Band*, Washington, D.C., RTCA DO-235B, March 13, 2008.

[7]   ARINC, *Global Navigation Satellite System (GNSS) sensor*, Annapolis, MD, ARINC Characteristic 743A-4, Dec. 2001.

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[9]   RTCA, *Minimum Operational Performance Standards for Airborne Supplemental Navigation Equipment Using Global Positioning System (GPS)*, Washington, D.C., RTCA DO-208, July 1991.

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[13]   FAA, *Stand-Alone Airborne Navigation Equipment Using the Global Positioning System Augmented by the Satellite Based Augmentation System*, Technical Standard Order (TSO) C146c, Federal Aviation Administration, Washington, D.C., 9 May 2008.

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[15]   FAA, *Ground Based Augmentation System Positioning and Navigation Equipment*, Technical Standard Order (TSO) C161a, Federal Aviation Administration, Washington, D.C., 17 December 2009.

[16]   RTCA, *Minimum Operational Performance Standards for Global Positioning System Local Area Augmentation System Airborne Equipment*, Washington, D.C., RTCA DO-253C, December 16, 2008.

[17]   U.S. Air Force, GPS Directorate, Los Angeles Air Force Base, *Navstar GPS Space Segment/User Navigation User Interfaces*, El Segundo, CA, IS-GPS-200D, Mar. 2006.

4. Subtask 4 - Receiver Performance Metrics

Task Statement

Develop appropriate metrics to quantitatively and qualitatively assess performance degradations from both technical and operational perspectives.

Overview

The metrics used to assess performance of a receiver depend on both its intended application and the type of output the unit provides. Regardless of the type of unit under test, a signal quality metric such as carrier to noise density ratio (C/N_0), if available, is valuable to include in an evaluation because this type of metric can be extended to determine how GNSS signals at varying elevation angles will be affected in a given receiver and antenna system so performance under varying constellation and environmental conditions can be predicted.

Although the metrics of interest for a particular receiver ultimately depend both on its available output and on its operational requirements, some types that can be used in evaluating degradation effects are listed here.

- Signal strength or quality
- Pseudorange and carrier phase measurement quality
- Carrier phase measurement continuity
- Automatic gain control characteristics
- Position/Time quality

Quantities related to these metrics are collected or calculated at a rate of 1 Hz or higher (each metric as possible by receiver) and then correlated in time to LightSquared signal power present at a specified point in the receive chain (for example, at the input to the antenna filter/LNA). Position quality results may be presented as scatter plots of positions collected at various LightSquared power levels and compared to similar constellation/environment conditions without LightSquared signals present. Other results may be plotted or tabulated according to LightSquared power levels with any significant receiver degradation events indicated as appropriate. More detail on each type of metric follows.

Signal strength or quality

The preferred measurement of signal strength or quality is carrier to noise density ratio (C/N_0) but any related metric may provide insight into how the receiver perceives its operating environment at different LightSquared signal power levels. Although the presence of a strong LightSquared signal at the edge of the GNSS L1 frequency band may invalidate some receiver assumptions in computing a signal quality indicator, it still may be pertinent because some receivers use this type of indicator to determine whether required levels for acquisition and/or tracking are being met. Still, concerns regarding signal quality indicator validity may be addressed through further analysis of corresponding pseudorange and carrier phase noise.

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Pseudorange and Carrier Phase Measurement Quality

A typical measure of pseudorange or carrier phase measurement quality is standard deviation of error, which is a quantity output by some receivers but can be computed for any receiver that outputs the pseudorange and/or carrier measurements with adequately high precision (typically within 0.001m). This type of metric can serve along with the signal strength or quality metric to observe changes in degradation as the received LightSquared signal strength changes.

Carrier Phase Measurement Continuity

Carrier phase measurement continuity metrics such as lock time and carrier phase cycle slips may be evaluated if the intended application of the unit under test involves carrier phase measurement processing, as in pseudorange smoothing or carrier-based positioning. Measurements may not be usable if excessive cycle slips or losses of lock occur in such applications, even if a receiver shows it is able to track satellites.

Automatic Gain Control Characteristics

For receivers that output information on automatic gain control (AGC), this metric adds insight into receiver response to LightSquared power near the edge of the GPS L1 band. Performance of some types of receivers may be limited by how the AGC reacts to the presence of strong interference and it can be useful to see if any AGC characteristics (e.g. gain, A/D bin distribution) are correlated with degradation seen in other metrics.

Position/Time Quality

Although position quality depends on other factors in addition to the presence of RFI, position quality metrics with and without the LightSquared signal present can be compared for receivers that can accommodate testing the same simulated GNSS scenario multiple times. This type of metric can be useful for receivers that do not output the lower level measurements used in the other metrics. Standard deviations of latitude, longitude and height are appropriate metrics for a laboratory scenario in which all GNSS signals are simulated at similar power levels. Position dilution of precision (PDOP) is an additional metric appropriate for scenarios in which simulated satellite power levels vary by elevation angle according to antenna characteristics and environmental conditions. If using live GNSS signals with and without LightSquared signals present, position quality comparison still can be done since the constellation tends to repeat each sidereal day – this, however, typically is not as consistent as repeating a simulated scenario.

Timing receivers also can undergo related types of tests involving standard deviation of time and time dilution of precision (TDOP), particularly if lower level measurements related to other metrics are not available.

5. Subtask 5 - Analysis of Effects to GPS Applications

Task Statement

Analyze the expected and potential effects of GPS use for each of the developed scenarios including current and future spectrum environment (e.g. 2025) considerations.

Overview

GPS susceptibility tests were conducted with various LightSquared signals and test environments. Testing was accomplished with conducted emissions in laboratory environments and radiated emissions in anechoic chamber and with Live Sky environments. During the course of this testing, over a dozen different types of receivers for applications ranging from aviation, survey to space were tested. **Table 5-1** provides the LightSquared power level where receivers indicated 1 dB degradations in C/No and when satellite tracking was disrupted (loss of lock). These results are for a single LightSquared base station and do not attempt to address aggregate power from multiple base stations (this is accomplished for specific applications in Task 6.) In addition to the Phase 0 through 2 LightSquared signal types, results from 10 MHz low are also provided in this Table. The results represented in this Table were generally taken from a single test environment versus providing a range of results for various test efforts. For example, the aviation receiver results were obtained from conducted emissions tests conducted at Zeta even though many of these same receivers were also used in Chamber and Live Sky testing. For completeness though, all test reports are included in this Subtask.

The summary Table for Task 5 in the main body of document was derived from these results using free space loss calculation and assuming a per channel EIRP of for LightSquared of 62 dBm and frequency of 1550 MHz.

Table 5-1. Degradation Effects * Caused by LightSquared Signals

Receivers	Phase 0	Phase 1	Phase 2	10 MHz Low
Aviation (conducted emissions)				
#1	-36/-28	-36/-28	-33/-24	-1/+3
#2	-62/-55	-63/-56	-60/-53	-2/+1
#3	-50/-48	-50/-48	-48/-45	-2/+2
#4	-35/-27	-38/-34	-38/-34	-4/+2
#5	-38/-21	NM	NM	NM
#6	-36/>-16	NM	NM	NM
#7	-30/-17	NM	NM	NM
Maritime (chamber tests)				
Timing (chamber tests)				

#8	NM	-55/-17 dBm	NM	NM
High Precision (chamber & live sky tests)				
#9	-32/-21	-54/-50	-46/-42	-27/-20
#10	-28/-21	-52/-47	-46/-42	-7 dBm/NA
#11	TBR/-24	TBR/-41	TBR/-39	TBR/-20
#12	-53/-41	-57/-52	-56/-50	-39/-27
#13	-43/-32	-51/-46	-50/-44	-20/-6
#14	TBR/-23	TBR/-43	TBR/-40	TBR/-21
#15	NM	-60/-46	NM	NM
#16	NM	-69/-43	NM	NM
Space (conducted emissions)				
TRIG	-76/-62	-84/-70	NM	NM
IGOR	NM	-60/-48	NM	NM

*data entries represent levels for (-1 dB C/No)/(Loss of tracking) values

TBR – data still being analyzed

Conducted Emissions Testing

FAA

Test Environment

GPS simulated signals were generated using a Spirent STR2760 or an Advanced Global Navigation Simulator (AGNS) calibrated to provide known signal levels (changed simulators because STR2760 power supply failed). For MOPS-based tests, broadband white noise was generated using an HP346B noise source that was amplified and then attenuated with a programmable attenuator to provide a controlled amount of additional noise. This broadband noise emulates the degradation of numerous sources that are not present for conducted tests and includes the energy of all other GNSS signals and sky noise.

The simulated GPS constellation used consists of 24 satellites plus one or two SBAS GEOs generating L1 C/A code, appropriate for MOPS-based tests and consistent with GPS SPS PS and DO-229 (SBAS simulated only for SBAS message loss tests). The constellation was generated from the Yuma almanac file from April 8th, 2009, with PRNs 01, 06, 18, 24, 25, 26, 32 removed and the GPS week changed to 1634. The power level of the simulated GPS signals depended on the type of test. For the ground-based receiver tests (Receivers #5, 6 & 7), the level was set to the SPS minimum of -128.5 dBm, assuming 0 dBi antenna gain. For the aviation receiver MOPS-based tests, one satellite was at -120 dBm and the rest were at -134 dBm, representing maximum and minimum levels at the input to a representative antenna filter/LNA. Note that in the MOPS-

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based tests, the receivers were allowed to track for approximately 15 to 30 minutes with all satellites at -120 dBm before dropping power of all but one to -134 dBm at the start of the test.

Although the tests of ground-based receivers did not include additional noise, the MOPS-based tests of aviation receivers required additional broadband white noise according to the MOPS-based test plan [1]. For the carrier-to-noise ratio (CNR) degradation test to determine a 1-dB degradation point, -173.5 dBm/Hz external noise was specified, which required adding 4.1 dB additional noise to the system. For the SBAS message loss tests, -170.5 dBm/Hz external noise was specified, which required adding 5.6 dB additional noise to the system. These noise levels are intended to emulate the highly stressful RF environment in which MOPS-compliant receivers are required to operate.

C/No 1 dB Degradation and Loss of Tracking Results

The 1 dB carrier to noise density (C/No) degradation and loss of tracking results for ground-based receivers are shown in Table 5-2. These were obtained with the Phase 0 LightSquared configuration and GPS signals at the SPS minimum level of -128.5 dBm. Note that Receiver #5 1-dB degradation result is at a point when the automatic gain control became unstable and caused a greater than 1 dB drop in C/No. Also Receiver #6 did not lose lock up to the maximum level tested, 16 dBm. Plots of the Phase 0 test results for Receivers #5, 6, & 7 are in **Figure 5-1**, Figure 5-2 and Figure 5-3, respectively.

Table 5-2. LightSquared Phase 0 Signal Power (dBm) for 1 dB C/No Degradation and Loss of Satellite Tracking

Receiver	1-dB C/No degradation	Loss of tracking
#5	-38*	-21
#6	-36	> -16**
#7	-30	-17

* G-II AGC gain shifted and C/No degraded by more than 1 dB at this level
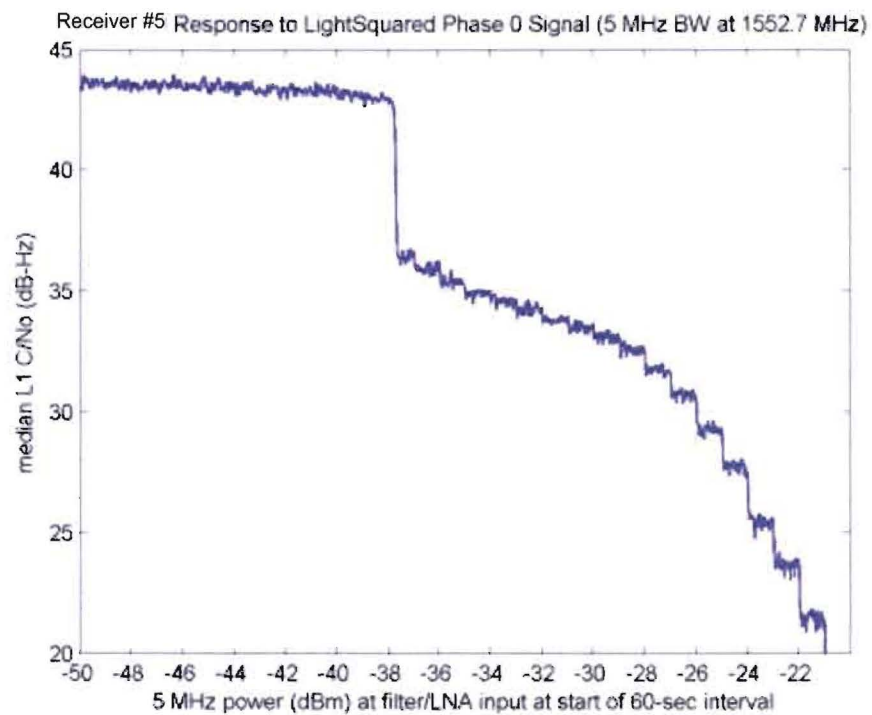** LGF did not lose lock at Phase 0 levels tested

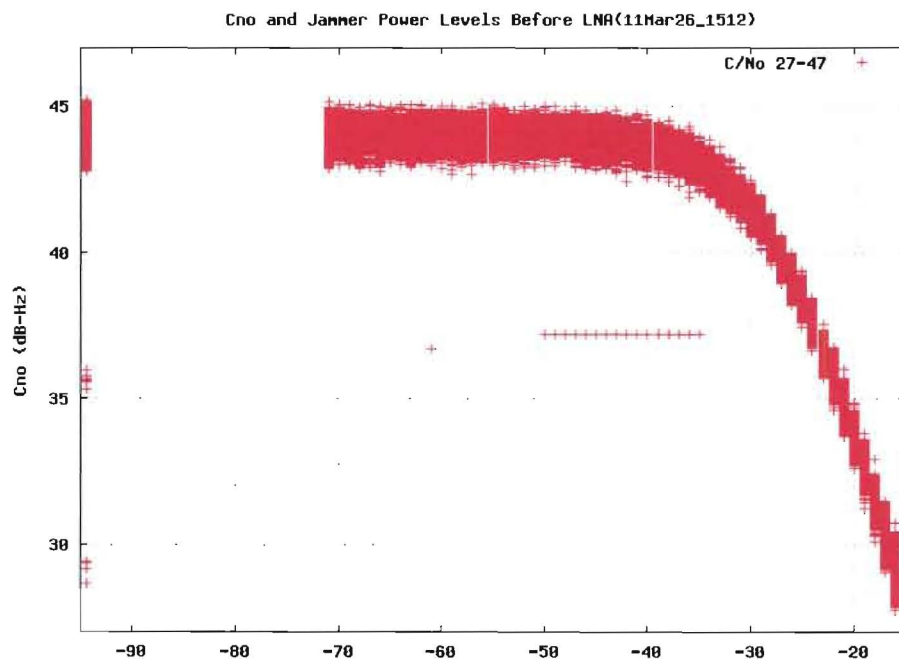**Figure 5-1.** Receiver #5 C/No Response to LightSquared Phase 0 Signal
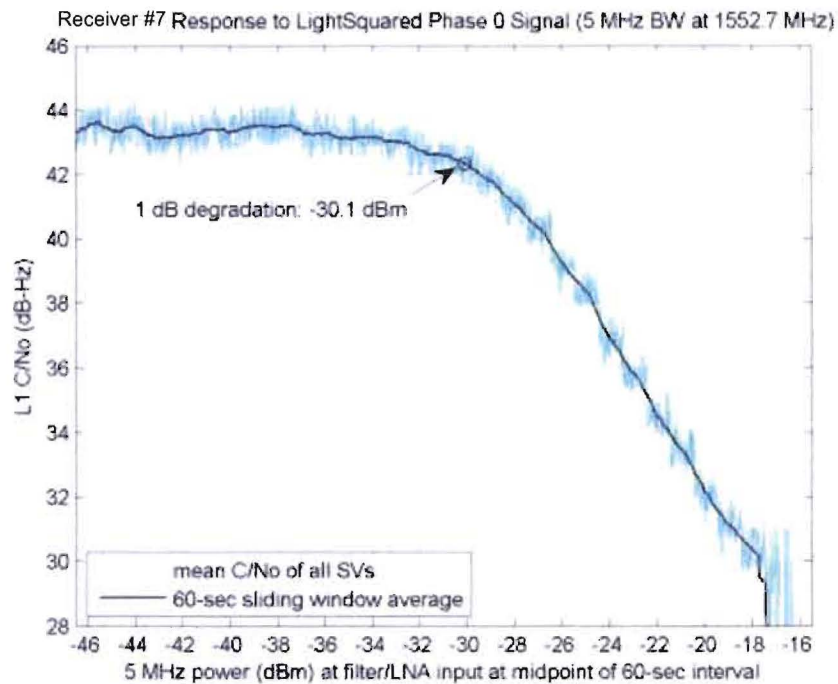

Figure 5-2. Receiver #6 C/No Response to LightSquared Phase 0 Signal

Figure 5-3. Receiver #7 C/No Response to LightSquared Phase 0 Signal

The 1 dB degradation and loss of tracking results for the aviation receivers obtained in the MOPS environment are shown in Table 5-3 and Table 5-4, respectively. The results cover LightSquared Phase 0, 1 and 2 configurations as well as two configurations using 5 MHz and 10 MHz bandwidths in the lower channel; the two low-channel configurations are the Phase 1 and 2 configurations without the upper channel included. Note these tests used GPS signals at low power, -134 dBm, and were conducted with the noise generator providing and equivalent external noise level of -173.5 dBm/Hz. Corresponding plots of the aviation receiver results are provided in Figure 5-4 through Figure 5-23.

Table 5-3. Signal Power (dBm/channel) for 1 dB C/No Degradation Caused by LightSquared Signals

Receiver	Phase 0	Phase 1	Phase 2	5 MHz Low	10 MHz Low
#1	-35.9	-35.9	-33.3	+3.4	-1.1
#2	-61.9	-62.5	-59.7	+3.7	-1.7
#3	-50.2	-50.0	-47.7	+2.9	-1.7
#4	-35.4	-38.2	-37.7	-1.0	-4.4